Hunukumbure, M. R., Beach, M. A., & Allen, B. (2002). Down-link beamforming effects on the code orthogonality in UTRA-FDD systems. In 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2002 (PIMRC), Lisbon Portugal. (Vol. 1, pp. 310 - 314). Institute of Electrical and Electronics Engineers (IEEE).

DOWN-LINK BEAM FORMING EFFECTS ON THE CODE ORTHOGONALITY IN UTRA-FDD SYSTEMS

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Abstract – A novel approach in quantifying code orthogonality factor for UTRA-FDD systems is extended in this paper to include the impact of down-link beamforming. The effects of fixed beam forming on code orthogonality is analysed through the aid of real channel data taken from urban cellular environments. The results show a significant overall improvement in code orthogonality with beam forming, especially in the case of an urban large cell.

Keywords – Code orthogonality, Beam forming

I. INTRODUCTION

Within the 3rd Generation UTRA-FDD standards, synchronous transmission in the down-link is employed within each cell in order to exploit the orthogonality of the spreading codes [1]. Due to its high chip rate at 3.84Mbps, several multi-path components in the radio channel can be resolved at the mobile receiver. These multi-paths provide a diversity gain through coherent Rake combining, but they can also lead to inter-path interference, which compromises code orthogonality. The degradation is quantified by the code orthogonality factor (denoted by α) and is directly related to an increase in intra-cell interference. This in turn will limit the cell capacity at a required performance level.

In this paper, a novel derivation for the code orthogonality factor (published in [2]) has been extended to investigate the effects of down-link beam forming. A review of the code orthogonality derivation is presented in section II. This mathematical model is modified in section III to incorporate a fixed beam forming architecture in the down-link. Using the derivations, code orthogonality factors are calculated for real channel data taken from urban cellular environments, in section IV. This is followed by a comparative analysis of code orthogonality with and without beam forming. Section V contains the key conclusions that can be drawn from this study.

II. CODE ORTHOGONALITY DERIVATION

A. Down-link SIR Estimations

The derivation is based on relating the intra-cell Signal to Interference ratio (SIR) in the down-link channel to its code orthogonality. The Signal and Interference power estimations are quoted from a study of the orthogonal spreading codes in a DS-CDMA forward (down) link by Adachi [3]. Assuming perfect alignment to path delays and perfect channel estimation, the signal power (*S*) captured by an M finger Rake receiver employing maximal ratio combining is given by;

$$S = (pg)^2 . P . \left(\sum_{m=1}^{M} \left| \xi_m \right|^2 \right)^2 \qquad (1)$$

Where P is the average received power, ξ_m gives the path gain coefficient for the mth selected path and (*pg*) refers to the processing gain.

In a multi-user environment that employs orthogonal spreading, the intra-cell interference *(I)* experienced by the wanted user is given by;

$$I = pg.P.\left[\begin{array}{l} \left\{ \sum_{m=1}^{M} \left(\sum_{l=1}^{m-1} 4.\mathrm{Re}^2\left[\xi_m^* \xi_l \right] \right) + \left| \xi_m \right|^2 \sum_{l=M}^{\infty} \left| \xi_l \right|^2 \right\} \\ + (C-1) \left\{ \sum_{m=1}^{M} \left| \xi_m \right|^2 . \sum_{l=1}^{\infty} \left| \xi_l \right|^2 - \sum_{m=1}^{M} \left| \xi_m \right|^4 \right\} \end{array} \right] \qquad (2)$$

Where *C* is the total number of users in the cell or sector, ξ_l are path gain coefficients for the infinite number of resolved paths (in a generalised case), * denotes complex conjugate and Re^2[ ] denotes the squared real part.

The first term relates to the self-interference (I_s), and the second term gives the multiple access interference, or MAI (I_m). It should be noted that orthogonal spreading nullifies any MAI between identical multi-paths (i.e. at the point of synchronisation). Equation (2) assumes that the same spreading factor is employed for all users and they are all received with equal power. Any noise (AWGN) contribution is excluded, assuming the system to be interference limited.

B. SIR in the reference channel model

For fixed system parameters of pg, P and C, the intra-cell Signal to Interference ratio (*SIR*) will entirely depend on the radio channel path gains. A lower value of SIR will indicate a greater loss of orthogonality and vice versa. The derivation attempts to quantify this relationship, considering a hypothetical uniform channel response consisting of N resolvable multi-paths as the 'worst case' reference. The magnitude of all N components will be identical and the phase will be uniformly distributed.

Denoting $|\xi_1| = |\xi_2| = \ldots = |\xi_N| = \gamma$,

$$S = (pg)^2.P.\left(\sum_{m=1}^{N} |\xi_m|^2\right)^2 = (pg)^2.P.\gamma^4.N^2 \qquad (3)$$

The interference power components (I_s) and (I_m) are calculated separately. In this uniform impulse response context, only the term $\mathrm{Re}^2[\xi^*_m \xi_l]$ in (I_s) is a random variable. As shown in [2], the interference power (I) simplifies to,

$$I = I_s + I_m = (pg).P.C.\gamma^4.N(N-1) \qquad (4)$$

Thus the *SIR* for the uniform impulse channel model is given by,

$$SIR = \frac{(pg)}{C}.\frac{N}{(N-1)} \qquad (5)$$

For N=1, the *SIR* tends to infinity and correspondingly there is no degradation of the orthogonality (i.e. α=1). When N is very large, the *SIR* approaches the value $(pg)/C$. Now the orthogonality is severely degraded (i.e. $\alpha \Rightarrow 0$). Based on these observations the orthogonality factor is quantified as,

$$\alpha = \frac{1}{N} \qquad (6)$$

The uniform impulse channel model provides a simple relationship between the orthogonality factor and the number of impulses. In dealing with real channel responses, the objective is to find an equivalent uniform impulse response (albeit with a fractional number of impulses), through their *SIR* calculated through equations (1) and (2).

III. QUANTIFYING CODE ORTHOGONALITY WITH DOWN-LINK BEAM FORMING

In this section the derivation is extended to incorporate the effects of down-link beam forming. With down-link beam-forming, the intra-cell SIR will improve due to 2 reasons. Firstly, the spatial filtering effect will reduce the interference. Secondly the delay spread and temporal variations of the channel will be reduced due to the suppression of multi-paths with wide angular spread and the enhancement of dominant paths. It is only the latter reason that should contribute to an improvement (if any) in code orthogonality.

A. The Spatial filtering factor

The spatial filtering effects are added to the reference uniform impulse channel model by introducing a spatial filtering factor (F). Hence the SIR in equation (5) is modified as;

$$SIR = F.\frac{pg}{C}.\frac{N}{(N-1)} \qquad (7)$$

Any SIR improvement beyond this value is due to reductions in channel delay spread and temporal variations. This will be reflected in code orthogonality.

In an idealized beam-forming scenario with M 'top hat' modelled main beams and uniformly distributed interfering users, the SIR will improve M times (i.e. F=M). In a practical system, there are 3 loss factors as identified in [4], which will diminish this gain. Namely, the Radiation loss (L_{RAD}), the Azimuth spread loss (L_{AS}), and the Cusping loss (L_{CUSP}). L_{RAD} is determined by the radiation pattern of the antenna array. L_{AS} is based on the azimuth spread of the transmitting signal's directions of departure (DoD) which will finally reach a particular user. L_{CUSP} accounts for the curvature of the practical radiation patterns at a given DoD. The following definitions are used to quantify these loss factors.

$$L_{RAD} = \frac{Outage\ \ power\ \ from\ \ allotted\ \ segment}{Total\ \ power\ \ in\ \ the\ \ radiation\ \ pattern} \qquad (8)$$

The 'outage power' is due to side lobes and main lobe spillage. The allotted segment would be the azimuth range an ideal 'top hat' beam would cover.

To quantify L_{AS}, (for a particular user) the relative signal strengths of DoD components falling outside the allotted azimuth segment are assessed.

$$L_{AS} = \frac{Signal\ \ power\ \ outside\ \ allotted\ \ segment}{Total\ \ signal\ \ power\ \ in\ \ azimuth\ \ spread} \qquad (9)$$

In quantifying L_{CUSP}, the antenna gain at an azimuth location of a given DoD is weighted by its relative power. Antenna gains are normalised to the gain at the main beam apex.

$$L_{CUSP} = \sum_i \begin{array}{l} \textit{(Antenna gain of } i^{th} \textit{ DoD within alloted beam)} \\ \textit{* (power fraction of } i^{th} \textit{ DoD)} \end{array} \qquad (10)$$

Figure 1 depicts a fixed 4-element beam forming scenario, where the above loss factors are illustrated. The four beam patterns should ideally occupy the 30° segments only. The majority of signal power reaching this user is transmitted from main beam A, which is assigned to bear the user signal. The outage power, which generates L_{RAD} is marked on Figure 1 as the shaded region. The fraction of signal power falling outside the allotted segment is attributed to L_{AS}. The normalised antenna gain for DoD 2 is around 0.5, which weighted by the relative signal power in DoD 2 contributes to L_{CUSP}.

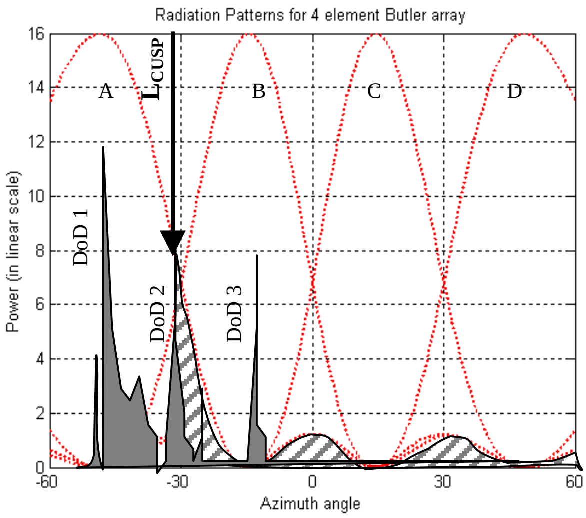


Figure 1: Illustration of loss factors in down-link beam forming

With these loss factors, the spatial filtering factor (F), for a practical beam forming system can be defined as;

$$F = M.(1 - L_{RAD}).(1 - L_{CUSP}).(1 - L_{AS}) \qquad (11)$$

B. Modifying the down-link SIR

The M beams in the fixed beam-forming scheme will concurrently carry different users depending on their azimuth locality. A given user will receive all the M beams with varying signal strengths. The allotted main beam for this user will carry the wanted signal and it will also introduce self-interference. The multiple access interference will come from all the beams. Hence in comparison to the single antenna scenario, only the term (I_m) in equation (2) needs to be modified as follows;

$$I_m = pg.\sum_{n=1}^{M} P_n C_n \left(\sum_{m=1}^{R} \left|\xi_{1,m}\right|^2 . \sum_{l=1}^{\infty} \left|\xi_{n,l}\right|^2 - \sum_{m=1}^{R} \left|\xi_{1,m}\right|^2 . \left|\xi_{n,m}\right|^2 \right) \qquad (12)$$

Where P_n is the received power (normalised to the signal power received from the allotted main beam) and C_n is the number of users for each of the M beams. Without loss of generality, it is assumed that the first main beam is to be allotted to the wanted user.

The SIR for radio channels with fixed beam forming can be calculated with the equations (1,2) but with a modified I_m, as above. This should be compared with SIR of equation (7) for the uniform impulse channel model, in order to obtain the code orthogonality factors.

IV. CODE ORTHOGONALITY CALCULATIONS

The code orthogonality factors are calculated for 2 different urban cellular environments, a small cell, and a large cell. The channel data was gathered through an extensive field trial campaign in Bristol, U.K. Using a state-of-the-art wide band vector channel sounder with an omni directional transmit antenna and an 8-element receiving antenna array, channel data in the 2GHz UMTS band was recorded. The receiver base station was located on a roof top. Here the channels are considered in the reciprocal sense, assuming the down-link base station to mobile transmissions. A full description of these trials can be found in [5].

The measurement procedure allowed 16 snapshots (instantaneous channel measurements) in the small cell and 8 snapshots in the large cell to be completed within channel coherence times. These measurement blocks are averaged to filter out the random noise effects. 100 such channel representations, spanning 10s duration are used to calculate the SIR for each mobile deployment and subsequently the code orthogonality values. The removal of channel noise is warranted because the noise effects are excluded in the derivation. In the initial results published in [2], the noise effects were present. The refined code orthogonality values presented in Table 1 are more realistic, being dependent only on multi-path and temporal channel behaviour.

Radio Environment	Number of mobile deployments	Code Orthogonality Factor (α)	
		Mean	Std. Dev
Urban Small	36	0.596	0.140
Urban Large	27	0.557	0.183

Table 1: Code orthogonality with single element antenna

The down-link system parameters are set at processing gain=64 (giving a symbol rate of 60kbps) and C as the number of mobile deployments. The Rake receiver is assumed to capture impulses within a 10dB power range.

The longer time of flight in the urban large cell allows more mulit-paths to be resolved at the Rake receiver. This is reflected in the lower mean value of code orthogonality. The standard deviations are high for both cells, suggesting that it is more appropriate to quote code orthogonality as a statistical figure.

For the beam-forming scenario, the channel data is further processed with 4 element and 8 element fixed beam-formers. The two urban cells are spilt into 120° sectors, for the application of beam-formers. The fixed beam-formers are implemented through 4*4 and 8*8 Butler matrices [6]. The number of users in each of the main beams is assumed to be the same, providing a uniform azimuth spread. This is expected to reflect the maximum possible gains with a beam-forming system. The signal directions of departure (DoD) from the base stations were calculated using a 2D ESPRIT algorithm [7], where multi-paths were detected across a 20dB dynamic range.

Figure 2 depicts a comparison of code orthogonality factors within the urban small-cell. The 3 plots shown are for a single antenna element system, 4 element beam-forming system and an 8 element beam-forming system.

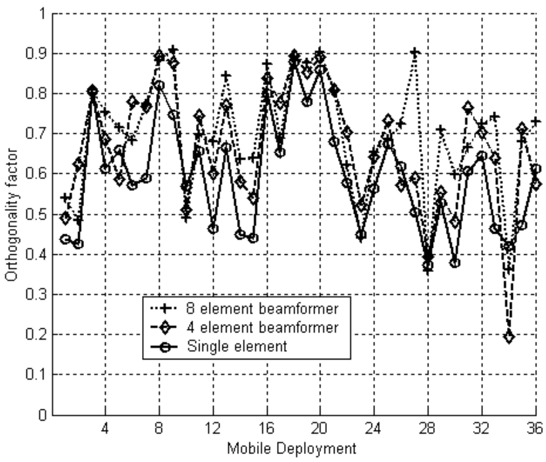
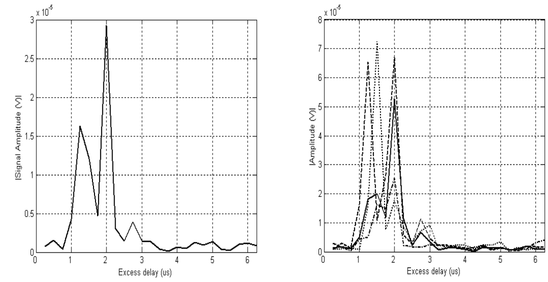


Figure 2: Code Orthogonality comparison - urban small cell

The mean code orthogonality value for the urban small cell improves by 12.9% to 0.670 with the use of a 4-element beam-former. If an 8-element beam-former is used, there is a 16.4% improvement of the mean orthogonality value to 0.694. This trend reveals diminishing gains for increasing the size and complexity of the beam-former. The standard deviation of orthogonality factors shows no significant change from the single antenna element scenario.

Interestingly, for a few mobile locations, beam forming has actually deteriorated code orthogonality. The worst case is at mobile deployment 34. To analyse the channel characteristics here, two representative impulse responses, one with the single antenna element and the other with the 4-element beam-former are presented in Figure 3.



(a) (b)

Figure 3: Channel impulse responses- mobile deployment 34
(a) Single element (b) 4-element beam-former

In figure 3b, the four impulse responses received via the four main beams are shown. All of them are with large magnitudes and more importantly there peaks show time offsets. The orthogonality of receiving OVSF codes via these impulses is severely degraded due to these time offsets. The spatial resolution of the single antenna channel in figure 3a, by the four fixed main beams has increased the delay spread. So in a fixed beam-forming system, there can be user locations that will experience a degraded service, through low code orthogonality. These are usually instances where the channels have a large azimuth spread or significant DoDs near main beam intersections.

The comparison of orthogonality values for the mobile locations within the urban large cell is presented in figure 4.

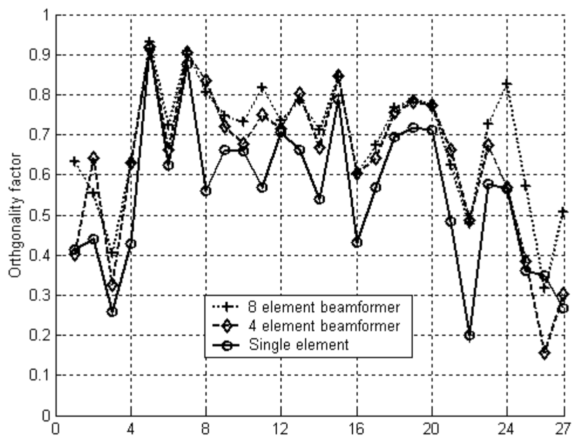


Figure 4: Code Orthogonality comparison - urban large cell

Within the urban large cell, the incorporation of a 4-element beam-former improves the mean code orthogonality by 15.3%, to 0.641. With an 8-element beam-former, the mean orthogonality factor goes up by 24% to 0.690. Here the level of improvement with beam forming is greater than in the small cell. There are more resolvable multi-paths in the large-cell (due to longer time of flights), hence their suppression through beam forming would have a greater effect. Also increasing the array sizes produce relatively higher antenna gains for the large cell. This will increase the range of coverage. As most of the large cell measurements were taken near the edge of the cell, this range extension would have helped to improve orthogonality by enhancing the received signal levels. Similar to the small cell, beam forming does not significantly change the standard deviation of code orthogonality values.

V. CONCLUSIONS

The inclusion of fixed beam forming to UTRA-FDD down link systems improves the overall code orthogonality, while they may deteriorate in certain channel locations. A fully adaptive beam forming strategy may overcome this limitation at the cost of increased system complexity. In general, the urban large cell shows a greater orthogonality improvement than the small cell, with down link beam forming. For both cellular environments, there is a high level of variance in the values of code orthogonality. This is not surprising, as the radio channel characteristics for different mobile localities can differ significantly. In this context it will be more realistic to quote code orthogonality values with a range of possible variations (as optimistic and pessimistic predictions), especially in a link level analysis.

ACKNOWLEDGEMENTS

The authors acknowledge the funding support under HEFCE JREI'98, which enabled the procurement of the Medav channel sounder, and Allgon systems AB, who provided the receiving antenna array for the field trial campaign. They are also grateful to Chor Min Tan, for modifying the 2D ESPRIT algorithm to suit to Medav channel data. M. Hunukumbure acknowledges his ORS award and the University of Bristol scholarship.

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